PARTE DOS

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Introduction

The Ibagué fault is a right lateral strike-slip fault that cuts obliquely across the Central Cordillera in a NE direction. Emerging from the eastern flank of the cordillera, the fault traverses the huge pleistocene alluvial fan of Ibagué over a distance of 35 km extending until the Magdalena river in the East (Figures 1 and 2). At this eastern end, the fault curves to the North to apparently merge with the N-S oriented Bituima-Salinas oblique West verging thrust system of the West flank of the Eastern Cordillera piedmont area.

Displacement along the Ibagué fault affects almost the entire width of the Central Cordillera and narrows the Magdalena Valley to the North of it (Montes et al. 2002; Acosta et al., 2004; Montes et al. 2005b). Along the 35 km stretch of the fault that traverses the Ibagué fan, it presents abundant morphotectonic features that are characteristic of strike-slip faults in an alluvial plain environment and which bear ample evidence of a high degree of activity during the Pleistocene (Diederix et al., 1987; Vergara, 1989; Montes et al., 2005b, Diederix et al., 2006).

In recent years the fault has been the subject of neotectonic and paleoseismologic studies undertaken by INGEOMINAS (Geological Survey of Colombia) for evaluating its past behaviour and seismogenic potential (INGEOMINAS, 2004; Montes et al., 2005a; Montes et al.; 2005b; Diederix et al.; 2006). This work included detailed neotectonic studies that resulted in a complete in-

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ventory of all morphotectonic features, their interpretation and kinematic modeling that permitted a qualitative evaluation of its degree of activity and led eventually to the selection of a suitable site for the excavation of a paleoseismologic trench (McCalpin, 1986; Audemard & Singer, 1987; Audemard, 2003a and 2005; INGEOMINAS, 2004). The opening of this trench, its logging and interpretation resulted in the quantification of the degree of activity of the fault during the Holocene; the results of which have been published (INGEOMINAS, 2004; Montes et al., 2005b; Diederix et al., 2006).

The present paper focuses on the method, the uncertainties and ambiguities of the method of paleoseismologic analysis applied, and the limitations and implications this might have for the evaluation of the seismogenic potential of the fault.

Regional geological setting

The Ibagué fault is considered to play a fundamental role in the seismotectonic framework of the so-called Northern Andean Block of Colombia, Ecuador and Venezuela, which is the result of complex interaction of the Nazca, Caribbean and South American plates (Pennington, 1981; Kellogg et al., 1995; Taboada et al., 2000; Arcila et al., 2002; Trenkamp et al., 2002; Cediel et ál, 2003) (Figure 1). The Ibagué fault is thought to fulfill a fundamental role as part of a transfer zone that affects both the Western and Central Cordilleras and possibly has an extension further to the East in the Eastern Cordillera (Ego et al., 1995; Montes et al., 2003 and 2005; Arcila, 2002; Acosta et ál, 2004; Taboada et al., 2000; Trenkamp et al., 2002, Cediel et al., 2003). This transfer zone relates to the collision of the Panama-Baudó arc with NW South America initiated approximately 8 million years ago during the Miocene (Figure 1) (Duque-Caro, 1980; Pennington, 1981; Ego et al. 1995; Taboada et al., 1998; Arcila, 2002; Acosta et al., 2002; Trenkamp et al., 2002; Audemard, 2003b; Montes et al., 2005; Cediel et al., 2003). It constitutes the dividing line between a left lateral transpressive seismotectonic regimes, to the North of the 4-5°N parallels, from a right lateral transpressive seismotectonic regime to the South. This happens along the N-S oriented Romeral and Cauca-Patía Fault Zone (RCPFZ), which traverses the entire length of the North Andean block along the western flank of the Cordillera Central (Ego et al., 1995; Acosta et al.; 2004, Montes et al., 2005; Cediel et al., 2003).

The Ibagué fault has been active at least since Pliocene times and probably since the Middle Miocene. Historical seismicity data indicate events in 1825 and 1942 with an intensity of VII on the Mercalli scale within the urban perimeter of the town of Ibagué, which is situated across the fault trace at the apex of the Ibagué fan (Ramírez, 1975; Gómez & Salcedo, 2000).

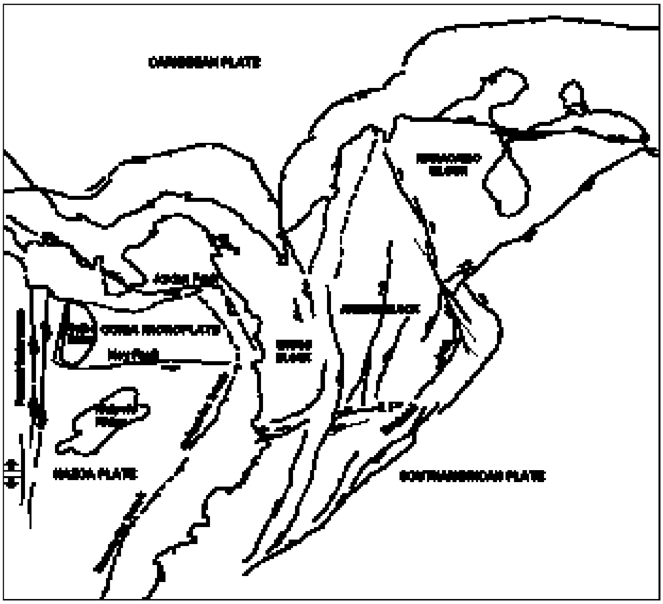

Figure 1. Geotectonic framework of the northern Andes and localization of the Ibagué fault zone. The arrows indicate the movements of plates relative to the stable South American plate (taken from: Trenkamp et al. 2002).

Morphotectonic indicators

Along the 35 km stretch of the fault that traverses the Ibagué fan between the Ibagué town in the West and the village of Piedras in the East, the fault trace is marked by an abundance of landforms that are characteristic morphotectonic indicators of active strike-slip faults in an alluvial plain environment (Figures. 2 and 3). Among these, one distinguishes fault scarps and scissored fault scarps, linear fault ridges, pressure ridges, fault benches and folds, controlled drainage, displaced and antecedent drainage, etc. (Diederix et al., 1987 ; Vergara, 1989 ; Montes et al., 2005 ; Diederix et al., 2006).

Of these features, the most common by far are the linear fault ridges and pressure ridges. Altogether 35 of these have been recognized, that vary in height between 3 m and 35 m and in length between 30 m and 1400 m. The linear fault ridges always straddle the fault trace and in rare outcrops display positive flower structure arrangements. The pressure ridges are associated with slight restraining bends in the trace of the principal fault plane (Sylvester, 1988; Diederix et al., 1987; Vergara, 1989; Diederix et al., 2006). The difference in sizes of the fault ridges is thought to be related to the varying thicknesses of the sedimentary column of the alluvial fan deposit that overly the basement (Diederix et al., 2006).

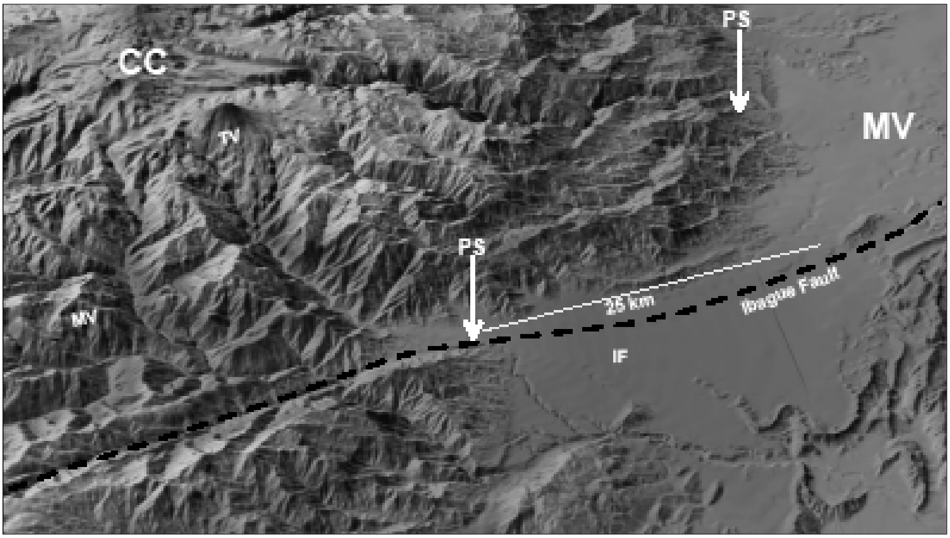

Figure 2. Physiographic shaded relief map based on STRM data of 30 m resolution. Note the tilted planation surface remnants in the east flank of the Central Cordillera (CC) and their right lateral displacement by the Ibagué Fault. Magdalena Valley (MV), Planation Surface (PS), Ibagué Fan (IF), Volcano Machín (VM) and Volcano Tolima (VT).

In contrast to the great abundance of fault ridges, the occurrence of pull-apart basins and associated sagponds is restricted to only three. Of course these, would be the obvious targets for the siting of exploratory paleoseimologic trenches, but unfortunately sagponds are also very much in demand as water reservoirs in use by the local farmers who have the habit of modifying these. Only one of the sites promised to be suitable. It was situated at a small releasing step-over, only partially ponded, located at the Los Gomos farm, the owner of which gave permission for the trench excavation (Ingeominas, 2002, Audemard & Singer, 1987, Audemard, 2003a and 2005)

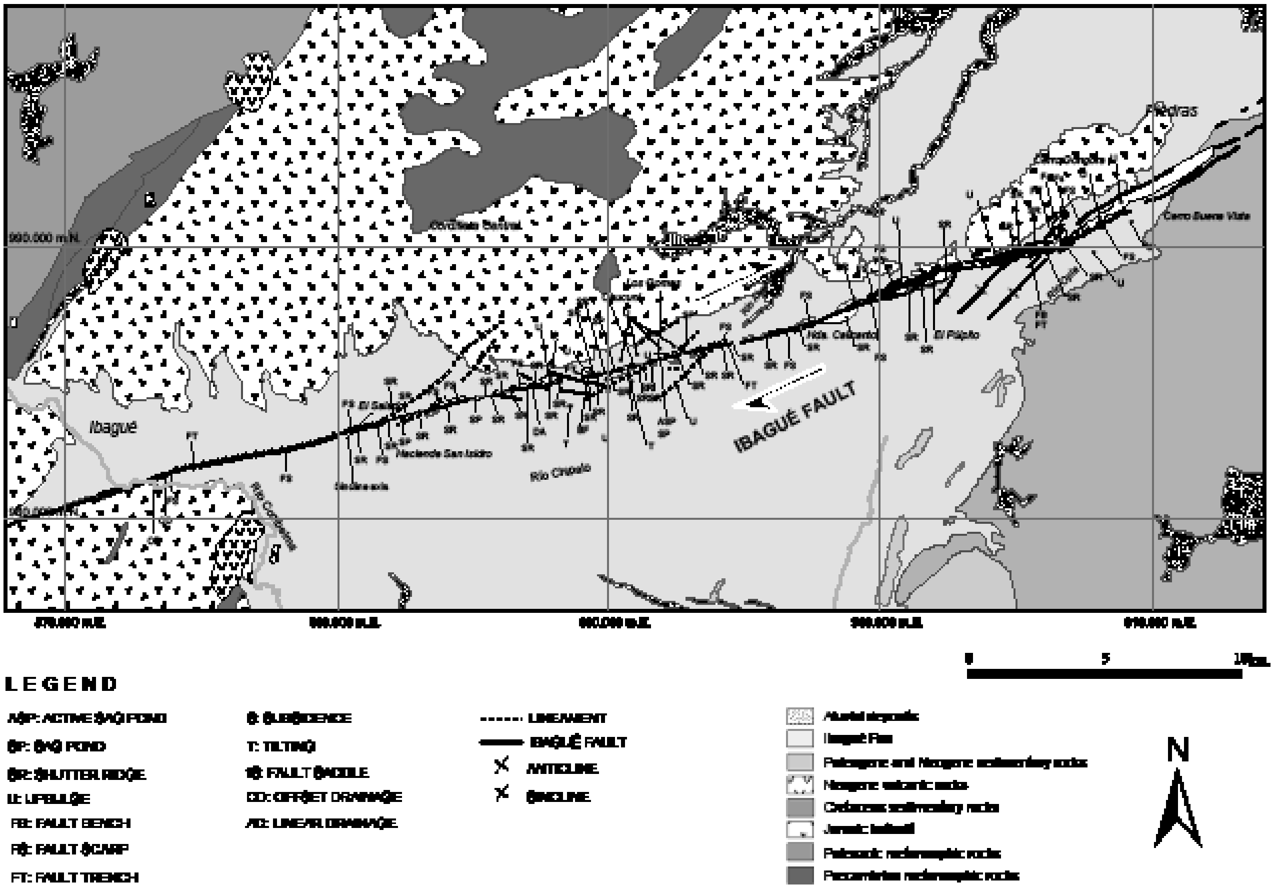

Figure 3. Strip map of the Ibagué fault where it crosses the main Ibagué fan, indicating the morphotectonic features.

In spite of the great abundance of morphotectonic indicators, very few of these present unequivocal criteria for establishing the sense and magnitude of strike-slip displacement. One such feature is a large pressure ridge at the Calicanto farm (Figure 3) where a process of kinematic adjustment (in fact a shortcutting or rectification of the principal fault trace) along the main fault plane, resulted in the longitudinal slicing and right lateral horizontal displacement of the North flank of the ridge and nearby drainage channel. Retrodeformation yielded a 565 m horizontal offset during Upper Pleistocene and Holocene times and an estimate for the slip rate of just over 5.6 mm/y for that period (INGEOMINAS, 2004; Diederix et al., 2006).

Another geomorphic marker of regional scale is the Miocene/Pliocene planation surface (peneplain) that truncates the Central Cordillera and has been tilted down to the East where it disappears under Pliocene formations and Quaternary alluvium of the Magdalena Valley (Page et al., 1981; Soeters, 1981; Diederix et al., 2006). This surface has been displaced horizontally and right laterally over a distance of 29 km by the Ibagué fault (Figure 2). A similar displacement has been observed in the Jurassic Ibagué batholith. It provides a reliable indicator of the sense and magnitude of displacement and yields an estimated slip rate for the Pliocene until the present of 5.8 mm/y, which agrees well with the findings for the displacement of the Calicanto pressure ridge (Diederix et al., 2006).

It is interesting to compare these qualitatively defined slip rates with the quantitative ones obtained from trench logging, which will be described in the following.

Paleoseismology

Trench

The selected site for trench excavation was situated in a shallow basin partially covered by a small pond, measuring approximately 60 by 80 m. This was interpreted to be a sagpond in a small pull-apart basin in a releasing right hand step-over along the main fault zone. At both ends of the basin are linear fault ridges that mark a right hand offset with respect to the orientation of the principal deformation zone (PDZ). The pond had not suffered any modification through human interference and its size apparently fluctuates somewhat with seasonal rainfall variation.

The trench site itself was chosen halfway between the pond and the Chucuní fault ridge so as to minimize the influence of coarse materials accumulated downslope of the fault ridge and to reduce the risk of encountering an elevated ground water level close to the pond (Audemard and Singer, 1987; Audemard, 2003a and 2005; INGEOMINAS, 2004). As it turned out none of these problems became a reality.

The layout of the trench was orthogonal to the strike of the principal deformation zone at the North rim of the basin close to the northern controlling fault strand of the step-over. The trench had a maximum length of 45 m and a maximum depth of 4.20 m. Its width at surface was 2.50 m tapering down to a width of 1.00 m at its deepest point, in order to achieve sufficient wall stability for safe working conditions. The length of the trench covered the basin depocentre, which was encountered between 30 and 35 m measured from the northern limit of the trench (Figure 4). Beyond the trench limit, the southern controlling fault of the basin was not intersected whereas, at the north end, the trench just touched the northern controlling fault zone, prevented from further extension by the presence of a fish pond.

The ground surface of the basin area displays a slight saucer shape with the central part being 1.50 m lower than the flanks on either side. In order to achieve a more precise location of the controlling faults, a microtopographic survey was carried out with the aid of a total station (EDM) as well as traverses with a radon gas emission receiver.

Stratigraphy of the basin fills

The basement of the Los Gomos pull-apart basin is made up of the same material as the top of the Ibagué fan deposit which has been down flexed and is present at a depth of 6.80 m in the deepest part of the pull-apart basin, as was established by extrapolation from the trench log. The deposits that make up the Ibagué fan consist of poorly sorted coarse gravels with lithic clasts and large blocks, mostly matrix supported, of predominantly andesites and to a lesser extent of paleozoic phyllites derived from the Central Cordillera. The matrix consists of fine-grained sands and argillaceous silts of a yellowish colour that have a volcanic ash component. The character is that of a sequence of

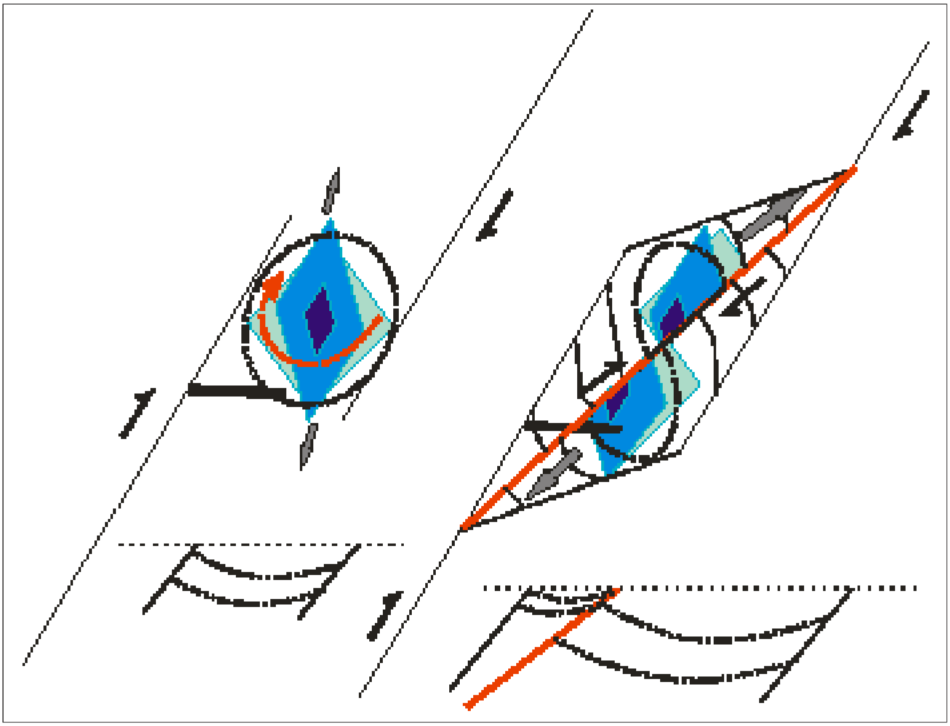

Figure 4. The Los Gomos trench site area, indicating the setting of the pul apart basin with sag pond in a right hand step over along the principal deformation zone (PDF). Note the diagonal cross basin fault, resulting from the kinematic adjustment process as well as the position of its intersection by the trench (fault zone B).

torrential gravels and mudflows of fluvioglacial origin, well consolidated and highly compacted that gives it a high degree of stability in exposed slopes. For this reason, it is possible that it has acted as a virtual rigid basement for the soft sediment infill of the basin with probable implications for the mechanical behaviour of faulting. The fan deposits have their origin in the volcanic pile of the Nevado de Tolima (5156 m), the stratovolcano that straddles the crest of the Cordillera Central. The Ibagué fan is largely of pleistocene age and in local depressions of the fan surface, there may be holocene infill as is the case in the Los Gomos pull-apart basin.

The base of the stratigraphic column of the basin fill starts with two levels (1 and 2) of fine to medium grained sand and gravelly sand that are separated by a horizon of residual pebbles (stone line), whereas at the base of level 1 a similar stone line is lying directly on top of the fan deposit. The sands have scarce content of scattered quartz pebbles and each level has a thickness of approximately 30 cm. The sands have probably been deposited in rather quiet conditions in a fluvio-lacustrine environment. Its deposition took place in two phases of subsidence, each triggered by a seismic surface rupture event.

Directly on top of it is a saucer shaped deposit of slightly olive green coloured silty clays that grade upwards into sandy clays and silts. It has a maximum thickness in the centre of 110 cm (level 3) (Figure 5). The base of this deposit is in erosional contact with the underlying sands, whereas towards the edge of the basin the deposit wedges out in a transgressive onlap relation against the side slope of the basin margin where it rests on the top of the fan surface (Figure 5). Its lithologic characteristics suggest a possible lacustrine anoxic environment of deposition. In the North flank of the basin, at the extreme northern limit of the trench, a small 40 cm high fault scarp indicates the presence of the controlling fault zone. This scarp is marked by the presence of a colluvial wedge consisting of transported fan materials that develops further downslope as a stone line underlying this unit (Figure 5). At the base of the deposit, a remnant patch of paleosol was encountered, that made possible to date the deposit.

On top of level 3 is a 3.50 m thick deposit of alternating dark grey to black strongly organic horizons with light grey less organic horizons in a sequence of 6 cycles (levels 4 to 9). Each cycle commences with the organic horizon at the base and the complete sequence reaches its greatest thickness in the depocentre of the basin. This is in the Southern half of the trench on the south side of a fault zone that divides the trench in two parts (see faulting and basin development section, P.). In the northern part, the sequence above the lowest organic level (level 4) is incomplete and depositional hiatuses have resulted in the merger of some levels into one.

The top level of the six cycles (level 9) has largely been removed by erosion. This erosion phase has been dated at approximately 700 y BP, and registers a change in climatic conditions from humid tropical to a drier seasonal climate indicated by the presence of ferruginous lateritic gravels and soils (levels 10 and 11). This change to drier conditions probably also marks the influence of men responsible for the removal of much of the forest cover. Just below this level, some potshards have been encountered.

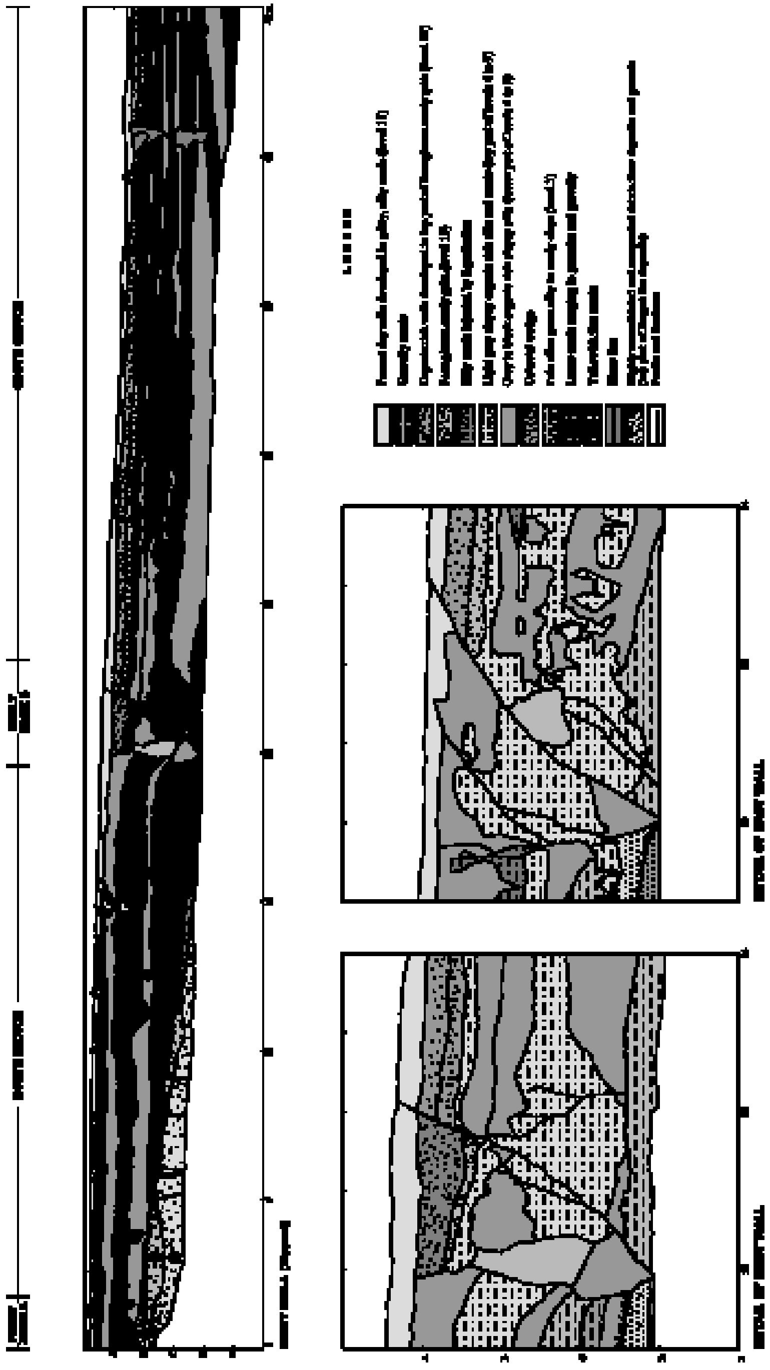

Figure 5. Trench log of the flipped west wall of the trench and details of the fault zone B on both trench walls.

At the South end of the trench, an open fissure occurs in both trench walls. This reaches from just below the present day top soil layer down to the base of the cyclic organic sequence (level 4) and is filled with material of levels 7, 8 and 10 as revealed by sample dates (Figure 5). This is an open crack generated by one or more surface rupture events (most likely events 9 and 10).

The depocentre of the basin is located in the deepest part of the Southern half of the trench where the entire sedimentary sequence is complete and reaches a thickness of 6.80 m. However, the base of the depocentre has not been exposed in the trench and consequently this figure is an approximation based on extrapolation of stratigraphic levels beyond the trench bottom.

No clear-cut evidence for the presence of seismites has been found as might have been expected to be the case in an environment of seismic shaking of soft sediments. However, there is evidence of liquefaction in cross cutting injection features in the cyclic organic rich sequence on both sides of the dividing fault zone B.

Sampling for C^{14} dating

Thirty samples for dating with the C^{14} method have been collected, most of these in the southern part of the west wall of the trench, covering the complete six cycle organic sequence. The samples were analyzed by means of the AMS method in the laboratories of Beta-Analytic in Miami. In this cyclic sequence, samples were taken at the bottom and top of each organic rich horizon. The oldest sample was collected from a remnant patch of paleosol situated on top of the stone line on the northern basin slope just underneath level 3. Older samples of organic remains were from mastodont bone fragments that had been found on top of the fan surface on the northern basin slope, but were not sent for C^{14} analysis. These are considered to range in age between 14 000 and 13 000 y BP. This agrees well with the date of the oldest paleosol sample of 12 630 to 12 960 y BP.

Additional sampling was carried out in the organic rich horizons of the incomplete sequence in the northern half of the trench, north of the cross-basin fault zone. This made cross fault stratigraphic correlations possible.

Within the zone of the cross-basin fault (fault zone B), four samples were collected and the results of these confirmed the complex mixing of different stratigraphic levels in this disturbed fault zone which makes pre-deformational reconstruction or retrodeformation virtually impossible.

Three samples were also collected from the open crack fill at the southern end of the trench. Results ranged in age from 1050-1300 y BP at the top to 2760-3160 y BP at the base, a somewhat puzzling outcome as the trench log indicated youngest soil material from the surface layers to be part of the infilling.

Depositional basin evolution

The saucer like synclinal shape of the basin is determined by the flexed down surface of the pleistocene Ibagué fan that marks the depression at this particular site. The top level of the fan deposit, which is exposed over the entire geographic extent of the Ibagué fan, constitutes also the more or less rigid basement of the basin at Los Gomos at the end of the Pleistocene. One assumes that, at the time of the opening of the basin, this top of the alluvial fan occupied the same position as the topographic surface of today in the same locality. Therefore the total depth of the basin of 6.80 m represents a real measure of the subsidence of the basin since approximately 15 000 y BP.

The saucer shape of the basin, very slight at surface, becomes progressively more marked with depth (Figure 7). The interpretative model of basin evolution is that of repeated and abrupt subsidence episodes related to an equal number of surface rupture events of M ≥ 6.5. This has resulted in periodic complete or partial infilling of the basin. Each abrupt change in sedimentation therefore correlates with a seismic event and the thickness of each sediment layer or cycle correlates with the magnitude of surface displacement.

The stratigraphic column indicates a threefold subdivision in the depositional episodes and the environment they represent (Figure 6). Thus, there is a first phase of infill representing the initial period of basin formation during the Upper Pleistocene. This is followed by the main phase of basin development, ponding and infill of richly organic sediments during the Holocene. At an early stage during this phase the newly formed cross-basin fault, strongly influenced the distribution of the sedimentation process. A third phase occurred in historic times when strong climatic and environmental changes caused the shrinking of the basin and a predominance of terrigenous sedimentation in much drier conditions that last until today.

During phase I of basin development, initial infill of the newly created basin was in the form of probably fluvio-lacustrine sandy to gravelly sediments deposited in two periods of rupture related subsidence. Progressive infill is registered by transgressive onlap relations of these sediments onto the basin margin slope. The final stage of phase I saw an extension of the basin area with the deposition of a rather thick deposit of a clayey to silty pale olive green deposit. The thickness of this deposit indicates a much wider area of infill as witnessed by the extensive transgressive onlap of it on the northern margin slope (Figure 5). The environmental depositional environment suggests possibly anoxic conditions in a rather cool climate and lack of aquatic organic growth at the very end of the Pleistocene.

The end of phase I and the beginning of phase II marked a profound change in the climate from cool rather dry conditions to humid tropical conditions and an expansion of the ponded area coinciding with the flourishing of abundant aquatic vegetation. Deposition was cyclic with repeated subsidence followed by gradual infill and abundant aquatic vegetation growth leading to gradual silting up and reduction in the dominance of this aquatic vegetation. Each cycle therefore begins with a dark organic rich horizon followed by a grey silty and less organic rich level. Six such cycles have been recorded in the depocentre area of the basin. At the end of the first cycle, the generation of a new basin-crosscutting fault (fault zone B) had a notable effect on basin configuration with the depocentre shifting sideways to the South (Figures 5 and 7) and the deposition in the northern sector becoming intermittent with hiatuses and merging of horizons in an incomplete sequence. Nevertheless, basin subsidence, although differentiated, continued over the entire width of the pull-apart basin area, by repeated and simultaneous down faulting of both the controlling basin margin faults and the new basin-crosscutting fault.

The last phase in basin development started with the erosion of the topmost layer of basin fill, a change in the environmental conditions, marked by dryer conditions with seasonally distributed rainfall and the reduction in the pond size. Soil development in a gravelly and gritty surface deposit is typical of terrigenous sediments and conditions very similar to those of today. Human influence, probably by extensive deforestation, must have been an important contribution to these new conditions.

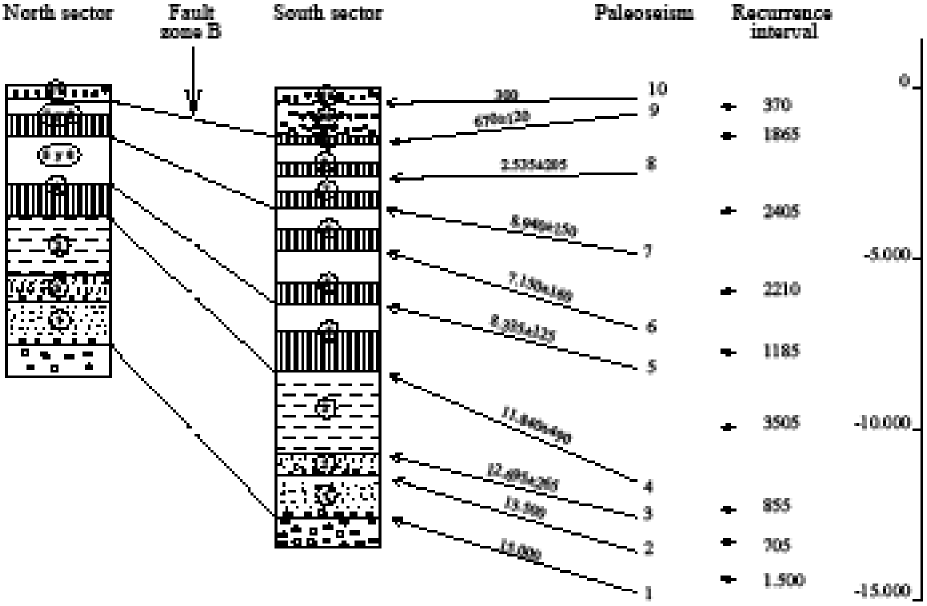

Figure 6. Stratigraphic columns of the north and south sector of the trench and their correlation across fault zone B. Indicated are the stratigraphic position and ages of paleoseismic events in the stratigraphic column as well as their recurrence intervals.

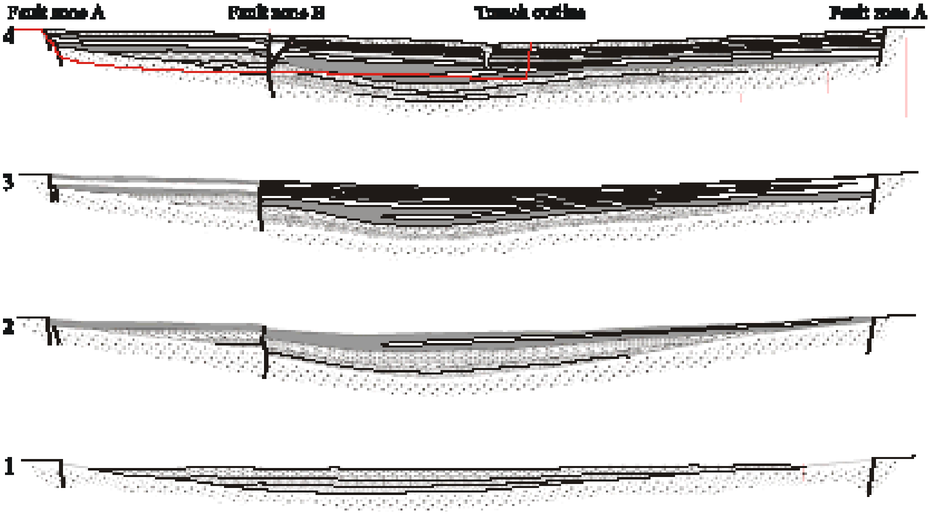

Figure 7. Schematic representation of four stages in the evolution of the pull apart basin. The outline of the trench has been indicated in stage 4. Also indicated are both basin side wall faults (fault zones A) and the cross basin fault (fault zone B).

The conclusion must be that, initially, during the first phases of periodic basin infilling (levels 1-4), subsidence was uniform across the entire width of the basin and was due to co-seismic slip along the controlling boundary faults. At the beginning of the Holocene, kinematic adjustment in the geometry of the faults caused the development of a new fault strand that cut diagonally across the basin (fault zone B), (Figs. 4 and 5). From that moment onwards, the principal strike-slip fault movement transferred to the new cross-basin fault with the earlier controlling basin sidewall faults playing a subsidiary role with mainly dip-slip or oblique slip displacement. This kinematic evolution bears similarities with the analog laboratory models described by Dooley and McClay (1997). Evidence for this development is that the complete sedimentary sequence, up to and including level 4, shows displacement by the new fault, which started operating after deposition of level 4, and can be easily correlated across the fault. But from level 5 upwards, this correlation is no longer straightforward because of partitioning of displacement over the new cross-basin fault and the earlier controlling faults. This has resulted in the sequence of the northern sector of the basin being incomplete. However, the thickness of each sedimentary cycle, as represented in the basin's depocentre, is thought to represent the sum total of vertical displacement along all faults and this constitutes the basis for the paleoseismic analysis.

A proviso has to be made with respect to the maximum thickness of the total sediment infill in the depocentre area, because in fact, excavation of the trench never touched the base of the basin. The total thickness of the stratigraphic column is therefore an estimate based on extrapolation from opposite sides of the basin slope angles and the thicknesses of levels 1, 2 and 3.

Faulting and basin development

The model adopted to explain the development of the Los Gomos pull-apart basin is that of a releasing right hand step-over in the principal deformation zone (PDZ) of a right lateral strike-slip fault. The basin is located in the open space between two linear fault ridges, the Chucuni ridge in the West and the Alcala ridge in the East. Co-seismic displacement along the controlling faults of the step-over caused the sagging of the area in the overlap zone and over the entire width of separation.

After the deposition of the first lacustrine organic rich sediment cycle (level 4), a new fault strand (fault zone B) became active and from then onwards most movement was concentrated along that fault, while the earlier controlling basin sidewall faults continued to act simultaneously. The new fault strand has an orientation diagonally across the step-over area more or less functioning as a short cut and is considered the result of a process of kinematic adjustment (Figure 4). This through going cross-basin fault zone is now acting as the PDZ and conforms rather well to the geometries and progressive evolution of releasing step-over basins studied in analog laboratory models by Dooley and McClay (1997). Similar kinematic adjustments have been observed in other localities along the Ibagué fault (i.e. the Calicanto pressure ridge–Par. 3) (Diederix et al., 2006) and in pull-apart basins along other strike-slip faults of Colombia (Diederix and Romero, 2008).

The trench intersected this new fault and in the log it was marked as fault zone B. It is a complex fault zone that has the characteristics of a flower structure with fault branches fanning out upwards. The stratigraphic units known from other parts of the trench occur in a confused juxtaposition within the fault zone, which is attributed to considerable along strike lateral displacements in a direction transverse to the trench wall. This complex juxtaposition is also confirmed by the C^{14} dates obtained in this fault zone, which present erratic distribution. In cross section it therefore presents both normal as well as reverse fault movement along the same fault branches. This situation makes cross fault correlation of stratigraphic units difficult and practically precludes pre-deformational reconstruction in an exercise of retrodeformation as is common practice in paleoseismologic trench interpretation (Audemard, 1996, 1997, 2005; Audemard & Singer, 1994, 1996; McCalpin, 1997; Burbank and Anderson, 2001).

This has motivated us to develop an alternative way of reconstructing the co-seismic deformation history of the basin. In this model, the registration of subsidence events is recorded in the sedimentation cycles that represent the repeated infilling of the basin. This means that each strata or cycle of two strata correlates to a co-seismic subsidence event. In this way, it was possible to differentiate 10 surface rupture events, eight of which have been age dated, with the oldest event dated at 12 960 y BP. Essential in this model is the assumption that the thickness of each unit or cycle is a direct measure of the magnitude of surface displacement.

Seismogenic potential

Slickensides on fault planes encountered in the trench as well as in other localities along the trace of the fault, have provided kinematic indicators that have yielded a consistent orientation of 10° S in the rake of striae on the slip surfaces. This made possible to convert vertical fault offsets into values for horizontal or oblique along strike displacements. Magnitudes per event were then calculated by using the equation proposed by Wells and Coppersmith (1994): $M = a + b^{*}\log(MD)$, where *a* and *b* are regression coefficients of a curve constructed on the basis of 43 well studied strike-slip fault ruptures worldwide, with a correlation coefficient of 0.9 and MD representing average displacement. Values for *a* and *b* have been established empirically by Wells and Coppersmith (1994) to be 6.81 and 0.78 respectively.

Co-seismic displacement based on sediment cycle thicknesses, varies between 35 cm and 120 cm. Applying the Wells and Coppersmith equation, these values correspond to magnitudes of M 6.8 and M 7.5 respectively. The average of all 10 vertical displacements would be 68 cm, and this corresponds to an average magnitude of M 7.3 per event. In a similar manner, the average slip rate over the last 15 000 years of recorded synsedimentary deformation has been calculated on the basis of total sediment thickness being 6.80 m, which corresponds to a total accumulated vertical displacement of the same value. This converts to a horizontal displacement of 38.70 m, yielding a horizontal slip rate of 2.58mm/y. This value is considerably higher than earlier estimates of 0.77 mm/y (INGEOMINAS, 2004). Corroboration of this slip rate can be found in the morphotectonic feature of the displaced Calicanto pressure ridge (Par. 3) and in the displacement of the Mio-Pliocene age planation surface that truncates the Cordillera Central (Par. **3**). Both yield slip rates in the order of almost 6 mm/y for the Plio-Pleistocene (Page et al., 1981, Soeters, 1981, Diederix et al., 2007). Besides, the lower slip rate for the Holocene, calculated from the trench data, is comparable to the difference in relative velocity between the kinematic vectors derived by Trenkamp et al. (2002) for the areas to the North and South of the Ibagué-Garrapatas transfer zone that marks a division in the North Andean block.

Based on 10 surface rupture events that occurred between approximately 15 000 y BP and 300 y BP, this gives an average recurrence rate of 1875 years with a variance between a maximum of 3505 years and a minimum of 855 years (Figure 6).

Another parametric aspect of importance that relates directly to the estimated magnitude per event has to do with the length of the rupture segment. Aerial photo interpretation and field surveys have indicated a 60 km long section of the fault, which is almost straight, having only a slight curvature. It stretches from the headwaters of the Cocora River in the Central Cordillera in the West to the village of Piedras at the east end of the fault in the very distal part of the Ibagué fan close to the Magdalena River (figs. 2 and 3). Over the entire length of this section, only minor echelon step-overs or restraining or releasing bends have been observed, but these are of insufficient dimensions to have functioned as active barriers to rupture propagation. This means that a rupture segment of 60 km length would confirm the seismic magnitudes established by trench data and compares well to fault segments of similar dimensions listed by Wells and Coppersmith (1994), known from other parts of the world (table I).

Discussion

The kinematic model for the development of the Los Gomos basin and pond is that of a pull-apart basin developed in a releasing step-over along a strike-slip fault. It has a separation of approximately 80 m and an overlap of unknown length but certainly not more than 100 m. It was not possible to verify this model completely because the trench did not cover the entire separation width and only just touched the northern controlling basin sidewall fault. However, the geometry of the wider area along this sector of the principal fault zone does not leave any doubt as to its pull-apart character in a releasing step-over.

The trench has intersected a major fault zone (fault zone B), which is not one of the two controlling faults, and has only been operative since the fifth seismic event. It concerns a secondary strike-slip fault that has been interpreted to be the product of kinematic adjustment that resulted in a straightening or rectification of the principal deformation zone (PDF) that transferred the main part of the displacement to the new strand with an orientation diagonally across the basin (Figure 4). This new strand is now the principal through going fault and geometrically functions as a cross-basin fault zone (Dooley and McClay, 1997). It has also resulted in a migration of the depocentre towards the south side of the new fault branch (Figures 4 and 7). Movement along the two controlling faults did not cease but was modified to dominantly dip-slip or oblique slip displacement. There is ample evidence that both the controlling sidewall faults and the new cross basin fault strand operated simultaneously. Dooley and McClay (1997) have described this model experimentally in the laboratory, achieving an analog model that strongly suggests similarities with the situation of the Los Gomos basin.

The correlation of stratigraphic horizons across the fault zone B in order to quantify displacement per event is difficult from level five upwards because of the horizontal along strike displacement of layers along this new fault zone, which practically precludes any plausible cross-fault reconstruction in vertical cross section. In addition, there is the impossibility of differentiating the contribution of each of the faults (that is the cross basin fault and the sidewall faults) to the sum total of displacement. This situation makes impossible to effectuate the classical retrodeformation exercise which is so common in paleoseismology (Audemard, 1996 and 1997; McCalpin, 1997; Burbank and Anderson, 2001; Audemard, 2003a, 2005). For this reason, we have opted for another method of analysis and interpretation that focuses on finding evidence for paleoseismic events in the stratigraphic column. In this model, the seismic history of the basin read in the sequence of sedimentary horizons (Marco and Amotz, 2005), where each deposition phase is the result of renewed subsidence triggered by surface rupture events. The top of each horizon or cycle is the event horizon and can be correlated to a seismic event. The thickness of each horizon or cycle is a direct measure of the magnitude of vertical surface displacement. It implies that the most complete seismic record, with respect to number of events as well as with respect to the magnitude per event, is to be found in the depocentre of the basin. There remains of course the uncertainty as to whether there has been a contribution by a-seismic movement. This remains an unknown.

The evident cyclicity in that part of the stratigraphic column, characterized by a sequence of organic rich dark horizons alternating with light grey less organic rich horizons, has been interpreted to be the result of repeated episodes of abrupt subsidence followed by an interseismic period of infilling of a shallow pond in humid tropical climatic conditions. The interpretation is that each sag creates new lacustrine conditions that favour the flourishing of abundant aquatic vegetation. This abundant aquatic growth diminished with progressive infilling of the pond. Unfortunately, it has not been possible to test this hypothesis by systematic granulometric, botanical and pollen sampling of the entire stratigraphic column. However, it is thought that the absence of such test data does not fundamentally undermine the validity of the model as presented here. Another restriction is that it has not been possible to date the two lower stratigraphic levels that constitute the base of the column and mark the start of the basin infilling, because of the absence of datable organic material in these sediments. Consequently, the dates given in figure 7 for the two paleoseismic events related to these two levels are speculative and the result of extrapolation.

Conclusions

The Ibagué fault represents an important seismotectonic element in the geodynamic evolution of the North Andean block of Colombia, which is an area of complex interaction of lithospheric plates and crustal blocks. The Ibagué fault is considered to be part of a transfer zone that plays a fundamental role in the stress transfer generated by the collision of the Panama-Baudó arc with the North Andean block, initiated during the late Miocene ± 8.0 my BP (Duque-Caro, 1990; Pennington, 1981; Kellogg et al., 1995; Taboada et al., 2000; Arcila et al., 2002; Acosta et ál, 2002; Trenkamp et al., 2002; Montes et al., 2005).

In this setting, the Ibagué fault has been active at least since late Miocene time when it started to displace dextrally the Central Cordillera over a distance of 29 km. This displacement took place for the major part during plio-pleistocene times and is best referenced by equal displacement of a pliocene tilted planation surface (peneplain) that truncates the Central Cordillera.

Along the 35 km long stretch of the fault that crosses the largely pleistocene alluvial Ibagué fan, it displays abundant morphotectonic evidence along its trace that reflects high degree of activity during the Quaternary. The results of paleoseimologic investigations carried out in a trench excavated in a small pull-apart basin with sag pond, which was preceded by detailed neotectonic surveys (INGEOMINAS, 2004; Montes et al., 2002, 2005a; Diederix et al., 2006), have corroborated quantitatively what earlier morphotectonic evidence had indicated qualitatively.

Paleoseimologic trench studies have yielded evidence for 10 pre-historic surface rupture events that have occurred since approximately 15 000 y BP with an average magnitude of M = 7.3, a fault slip rate of 2.8 mm/y and a period of recurrence of 1875 years.

The method of paleoseismologic analysis applied has been based on the use of stratigraphic indicators that rests on the premise that each stratigraphic level or cycle can be correlated to a paleoseismic surface rupture event that caused the periodic and abrupt subsidence of the basin and its subsequent infilling. In this model, the thickness of individual stratigraphic units provides a direct measure of the vertical component of co-seismic surface displacement. Kinematic indicators on slip surfaces encountered in the trench and other localities along the fault trace subsequently facilitated the conversion to values for lateral displacements and magnitude per event.

Furthermore, the geometric disposition of faults encountered in the trench has given rise to the development of a model that explains the progressive kinematic evolution of a fault system in a releasing step-over along a right lateral strike-slip fault.

The results obtained from this study give a clear indication of the seismogenic potential of the Ibagué fault, which proves to be considerably higher than thought until recently. The Ibagué fault is the first and only fault in Colombia for which systematic neotectonic and paleoseimologic studies, supported by an adequate number of C^{14} dating, have been undertaken, and for which pertinent data on past and possibly future behavior are now available.

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References

Acosta, J. (2002). *Structure, tectonics and 3D models of the Western foothills of the Eastern Cordillera and Middle Magdalena Valley, Colombia*. Publicaciones Especiales 25, Bogotá: INGEOMINAS, 213 p.

Acosta, J., Lonergan, L. & Coward, M.P. (2004). Oblique transpression in the Western thrust front of the Colombian Eastern Cordillera. *Journal of South American Earth Sciences* 17, 181-194.

Arcila, M., Muñoz, A. & De Vicente, G. (2002). *Análisis sismotectónico de la convergencia Caribe, Nazca y Sudamérica*. Primer Simposio Colombiano de Sismología. Bogotá: Instituto Colombiano de Geología y Minería. Memoria digital.

Audemard, F.A. (1996). Paleoseismicity studies on the Oca-Ancón fault system, northwestern Venezuela. In: Dewey, J. and Lamb, S. (eds.), Geodynamics of the Andes. Selected papers. 2nd International Symposium on Andean Geodynamics. Oxford, September 1993. *Tectonophysics*, 259, 67-80.

Audemard, F.A. (1997). Holocene and historical earthquakes on the Boconó fault system, southern Venezuelan Andes: trench confirmation. In: Hancock, P. & Michetti, A. (eds). Paleoseismology: understanding the past earthquakes using Quaternary Geology. Symposium on Paleoseismology at the XIV INQUA Congress, Berlin, August 1995. *Journal of Geodynamics* 24(1-4), 155-167.

Audemard, F.A. (2003a). Estudios paleosísmicos por trinchera en Venezuela: métodos, alcances, aplicaciones, limitaciones y perspectivas. *Revista Geográfica Venezolana*, 44(1), 11-46. Mérida: Universidad de los Andes.

Audemard, F.A. (2003b). Geomorphic and geologic evidence of ongoing uplift and deformation in the Merida Andes, Venezuela. *Quaternary International,* 101-102C, 43-65.

Audemard, F.A. (2005). Paleoseismology in Venezuela: objectives, methods, applications, limitations and perspectivas. *Tectonophysiscs* 408 (1-4): 29-61.

Audemard, F.A. & Singer, A. (1987). La ingeniería de fallas activas en Venezuela: historia y estado del arte. Fundación Venezolana de Investigaciones Sismológicas, pp.11-26.

Audemard, F.A. & Singer, A. (1994). Parámetros sismotectónicos para fines de la evaluación de la amenaza sísmica en el noroccidente de Venezuela. VII Congreso Venezolano de Geofísica, pp. 51-56.

Audemard, F.A. & Singer, A. (1996). Active fault recognition in northwestern Venezuela and its seismogenic characteristization: Neotectonic and paleoseimic approach. In:

Engdahl, E.R., Castaño,J. & Berrocal, J. (eds.), Proceedings of the 1994 Regional Seismological Assembly in South America. *Geofísica Internacional*, 35(3), 245-255.

Burbank, D.W. & Anderson, R. S. (2001). *Tectonic Geomorphology*. Blackwell Science, Oxford, U.K., 266 p.

Cediel, F., Shaw, R.P. & Cáceres, C. (2003). Tectonic assembly of the Northern Andean block. *AAPG.* Memoir 79, 815-848.

Diederix, H., Gómez, H., Khobzi, J. & Singer, A. (1987). Indicios neotectónicos de la Falla de Ibagué en el sector Ibagué-Piedras, departamento del Tolima, Colombia. *Revista del Centro Interamericano de Fotointerpretación*, 11 (1-3), 242-252.

Diederix, H., Audemard, F.A., Osorio, J.A., Montes, N., Velandia, F. & Romero, J. (2006). Modelado morfotectónico de la Falla de Ibagué, Colombia. *Revista de la Asociación Geológica de Argentina*, 61(4), 492-503.

Diederix, H. & Romero, J. (2008). Atlas de deformaciones cuaternarias de los Andes. Proyecto Multinacional Andino: Geociencia para las Comunidades Andinas.

Dooley, T. & McClay, K. (1997). Analog modeling of pull-apart basins. *AAPG Bulletin*, 81(11), 1804-1826.

Duque-Caro, H. (1995). The Choco Block in the northwestern corner of South America: Structural, tectono-stratigraphic and paleogeographic implications. *Journal of South American Earth Sciences*, 3 (1), 71-84.

Ego, F., Sebrier, M. & Yepes, H. (1995). Is the Cauca-Patia and Romeral fault system left or right lateral? *Geophys. Res. Letters*, 22(1), 33-36.

Gómez, A. & Salcedo, E. (2000). Atlas de Sismicidad Histórica de Colombia. Informe Interno. Bogotá: Instituto Colombiano de Geología y Minería, Ingeominas, 136 p.

Ingeominas, (2004). Paleosismología de la Falla de Ibagué. Informe interno. Bogotá: Instituto Colombiano de Geología y Minería, Ingeominas, 123 p.

Kellogg, J.N. & Vega, V. (1995). Tectonic development of Panama, Costa Rica and the Colombian Andes: constraints on global positioning system, geodetic studies and gravity. In: Mann, P. (ed.), Geologic and Tectonic development of the Caribbean plate boundary in Southern Central America. *GSA* Special Paper, 295, 75-90.

Marco, S. & Amotz, A. (2005). High resolution stratigraphy reveals repeated earthquake faulting in the Masada Fault zone, Dead Sea Transform. Tectonophysics, Special Issue: Paleoseismology: Integrated study of the Quaternary Geological Record for earthquake deformation and faulting, 408 (1-4), 101-112.

McCalpin, J.P. (1996). Paleoseismology. Academic Press, 494 p. San Diego, California.

Montes, C., Restrepo-Pace, P. &Hatcher, R.D. Jr. (2003). Three-dimensional structure and kinematics of the Piedras-Girardot fold belt: Surface expression of transpressional deformation in the northern Andes. In: Bartolini, C., Buffler, R.T. & Blickwede, J.

(eds.), The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation and plate tectonics. AAPG Memoir 79: 849-873.

Montes, C., Hatcher Jr., J.D. & Restrepo-Pace, P. (2005). Tectonic reconstruction of the northern Andean blocks: Oblique convergence and rotations derived from the kinematics of the Piedras-Girardot area, Colombia. *Tectonophysiscs* 399(1-4): 221-250.

Montes, N., Osorio, J.A., Velandia, F., Acosta, J. & Núñez, A. (2005). Caracterización sismogénica de la Falla de Ibagué, Colombia. Décimo Congreso Colombiano de Geología. Bogotá.

Montes, N., Velandia, F., Osorio, J.A., Audemard, F.A. & Diederix, H. (2005). Interpretación morfotectónica de la Falla de Ibagué para su caracterización paleosismológica. *Boletín de Geología*, 27(44), 95-114. Bucaramanga: Universidad Industrial de Santander.

Page, W.D. & James, M.E. (1981). The antiquity of the erosion surfaces and Late Cenozoic deposits near Medellin, Colombia: implications for tectonics and erosion rates. *Revista del Centro Interamericano de Fotointerpretación*, 6(1-3), 421-454.

Pennington, W.D. (1981). Subduction of the Eastern Panama basin and Seismotectonics of northwestern South America. *Jour. Geophys. Res.*, 86-B11, 10753-10770.

Ramírez, J. (1975). *Historia de los terremotos en Colombia*, Segunda edición. Bogotá. Instituto Geográfico Agustín Codazzi, 250 p.

Soeters, R. (1981). Algunos datos sobe la edad de dos superficies de erosión en la cordillera Central de Colombia. *Revista del Centro Ineramericano de Fotointerpretación*, 6(1-3): 525-528.

Taboada, A., Rivera, L.A., Fuenzalida, A., Cisternas, A., Philip, H., Bijwaard, H., Olaya, J. & Rivera, C. (2000). Geodynamics of the northern Andes: Subduction and Intracontinental deformation (Colombia). *Tectonics*, 19, 787-813.

Trenkamp, R., Kellogg, J.N., Freymueller, J.T. & Mora, H. (2002). Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. *Journal of South American Earth Science,* 15, 157-171.

Vergara, H. (1989). Actividad neotectónica de la Falla de Ibagué, Colombia. Memorias V Congreso Colombiano de Geología, I, 147-167. Bucaramanga.

Wells, D. & Coppersmith, K. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement. *Bull. Seis. Soc. Am.*, 84(4): 974-1002.